Transient Simulation of the Removal Process in Plasma Electrolytic Polishing of Stainless Steel

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1. Introduction

Plasma electrolytic polishing:
- Electrochemical method for surface treatment
- Special case of anodic dissolution [1]

Advantages:
- Environment friendly aqueous solutions of salts
- Small achievable roughness ($Ra < 0.02 \ \mu m$)
- Small removal rates
- Small processing times

Disadvantages:
- Mainly metal parts can be polished
- Energy source determines the maximum part size
- Each metal requires electrolyte adaption
1. Introduction

Challenges:

- Few research work has been focused on the understanding of the process and even less on simulation
- Complex combination of many physical phenomena
- The mechanism of the polishing process is not fully understood yet

Objectives:

- Investigate PeP process:
  - Potential distribution
  - Current density distribution near the workpiece surface
- Simulate polishing process during PeP
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2. Model description – Studies and couplings

- The model is based on the assumption that PeP can be considered as an electrochemical polishing.
- The simulation has two studies: stationary study and time-dependent study.
- Geometry deformation is function of normal current density on the surface:

\[ \nu_{\text{deform}} = K \cdot (-j_n) \]
2. Model description – Initial geometry and boundary conditions

- Ammonium sulfate in concentration of 50 g/l as an electrolyte [4]
- Steel 304 as material for the workpiece
- The thickness of plasma-gas is 150 μm
- Applied voltage of 200 V
- The initial anode surface profile was generated in COMSOL Multiphysics® using Spatial Frequencies method [5]
2. Model description – Plasma-gas layer conductivity and removal coefficient

- Based on the assumption, that almost all voltage drops in the plasma-gas layer

- Electrical field of $1.3 \cdot 10^4$ V/cm corresponds to values provided in literature: $10^4$ V/cm - $10^5$ V/cm [6-8]

- Removal coefficient K is calculated from experimental data: average material removal rate (MRR) and average current density for 200 V [4]

\[
E = \frac{V}{h} = \frac{200 \text{ V}}{0.015 \text{ cm}} = 13333 \text{ V/cm}
\]

\[
j_n = \sigma \cdot E
\]

\[
\sigma_{\text{plasma-gas}} = \frac{j_n}{E} = \frac{0.3399 \text{ A/cm}^2}{13333 \text{ V/cm}} = 2.55 \cdot 10^{-2} \text{ mS/cm}
\]

\[
K = \frac{\text{MRR}}{j_n} = \frac{5.24 \cdot 10^{-8} \text{ m/s}}{3398.69 \text{ A/m}^2} = 1.54 \cdot 10^{-11} \text{ m}^3/(\text{A} \cdot \text{s})
\]
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3. Results – Polishing effect and electric potential

Animation of the polishing process

Electric potential
3. Results – Polishing effect and electric potential

- The main voltage drop occurs in the plasma-gas layer.
- Despite the fact that the overall shape of the surface is conserved, the peaks were removed more.
- Because of voltage drops in plasma-gas layer, it can be considered as a special electrochemical cell, where the interface between plasma-gas layer and electrolyte acts as a cathode.
3. Results – Current density during polishing

- The normal current density in the cavities is lower than at the peaks
- The current density at the deeper cavities increases with the processing time
- Average current density in model is 0.313 A/cm$^2$ comparing to 0.340 A/cm$^2$ in experiment [4]
3. Results – Roughness calculation

- To analyse the polishing effect, the roughness parameter $Ra$ was calculated based on:

$$Ra = \frac{1}{l} \int_{0}^{l} |h(x)| \, dx$$

- Next component couplings were used: intop1 - integration over a boundary 19; p10 and p12 - maximum functions in points 10 and 12 respectively; aveop1 – average over a boundary 19
3. Results – Roughness calculation

- Equation used in the model for $Ra$ calculation

$$Ra = \frac{1}{(p12(x) - p10(x))} \int_{p10}^{p12} |y - \bar{y}| \, dx$$

- The roughness decreases in the model according to exponential decay, what corresponds to real experimental data [7]

- The minimal achievable roughness $Ra$ in this model based on the exponential fit has a value of 0.84 $\mu$m [7]
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- 2D simulation of the plasma electrolytic polishing
- PeP of stainless steel can be simulated as an electrochemical machining process
- Simulation of the polishing effect and removal process
- Implementation of $Ra$ calculation in the model

Next steps:

- Longer simulated time
- Comparison with experimental data
- Simulation with initial roughness from real sample
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Thank you for your attention


